Chapter 1
Beginnings of the Theory of Machines[1]

It is always fascinating to know the origins of any subject. The subject of Theory of Machines began during the era of James Watt with the Industrial Revolution. We will look at what happened prior to this.

1.1 Beginning of the Wheel

During the Mesolithic, or Middle Stone Age, some many thousands of years ago, man found that a section of a tree trunk could be moved more easily under the force of gravity because it was round. If the branches and twigs of the trunk were removed, the speed of the rolling log improved.

Early men began to place runners under a heavy load, which they discovered would make it easier for the load to drag. This was the invention of the sledge. Men then began to combine the roller and the sledge. As the sledge moved forward over the first roller, a second roller was placed under the front end to carry the load when it moved off the first roller. It was discovered that the rollers which carried the sledge became grooved with use and that these deep grooves actually allowed the sledge to advance a greater distance before the next roller was needed to come on. Thus, the rollers were changed into wheels. In the process of doing so, sections of wood between the grooves of the roller were cut away to form an axle and wooden pegs were fastened to the runners on each side of the axle. A slight improvement was made to the cart. This time, instead of using pegs to join the wheels to the axle, holes for the axle were drilled through the frame of the cart. Axle and wheels were now made separately.

The wheel is probably the most important mechanical invention of all time. Nearly every machine built since the beginning of the industrial revolution involves a single, basic principle embodied in one of mankind's truly significant inventions.

[1] This chapter is based on the paper "History of Rotating Machines", *IFToMM Workshop on the History of Machines and Mechanisms, HMM 2007*, Bangalore, December 14, 2007.

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It is hard to imagine any mechanized system that would be possible without the wheel or the idea of a symmetrical component moving in a circular motion on an axis. From tiny watch gears to automobiles, jet engines and computer disk drives, the principle is the same.

Agricultural villages had begun to develop by 8000 BC. This is known as the Neolithic period, or New Stone Age. During this time the slow potter's wheel was invented. In about 3000 BC Egyptians developed the fast wheel, a completely mobile, carefully balanced apparatus of stone. Based on diagrams on ancient clay tablets, the earliest known use of this essential invention was a potter's wheel that was used at *Ur* in Mesopotamia (part of modern day Iraq) as early as 3500 BC. The first use of the wheel for transportation was probably on Mesopotamian chariots in 3200 BC. It is interesting to note that wheels may have had industrial or manufacturing applications before they were used on vehicles.

The wheel was furthered improved on later by the Egyptians, who made wheels with spokes, which could be found on Egyptian chariots of around 2000 BC. Over in Ancient India, chariots with spoked wheels dating back to around 1500 BC were also discovered. The Greeks too, adopted the idea of wheel-making from the Egyptians and made further improvements to it. Later, during the time of the Roman Empire, the Romans too engaged themselves in wheel-making and produced the greatest variety of wheeled vehicles. They had chariots for war, hunting, and racing, two-wheeled farm carts, covered carriages, heavy four-wheeled freight wagons and passenger coaches.

With the collapse of the Roman Empire in AD 476, the wheel became widely used for war machines across the old empire. The grinding wheel was introduced from Arabia to Europe in the middle ages, greatly improving the effect of bladed combat weapons.

1.2 Archimedes (287–212 BC)

The first to systematize the simple machines and propound the theory of their functions was Archimedes of Syracuse in Sicily. It was probably he who invented the compound pulley, a device for increasing traction or lifting power and he propounded the theory of the lever, both one- and two-armed. He regarded the wheel as a circular figure described by a rotating one-armed lever, and the screw as the circular analogy of the inclined plane. One of his famous sayings is "Give me a place to stand and I will move the earth".

Archimedes received his education at the University of Alexandria, where groups of mathematicians and scientists worked, devoting themselves to the construction of numerous fascinating machines. The greatest and most colorful of what is known as the Alexandrian school of engineers was undoubtedly Hero who lived sometime during the second century BC. His best invention was the *aelopile*, the first reaction turbine, which converted heat into mechanical energy through the medium of steam.

Hero's *aelopile*, the first reaction turbine, could not produce useful work, as the speed was not sufficient to create the required high head of steam. In the 1780s James Watt worked on the theoretical operating conditions of a reaction turbine and he concluded that such a turbine could not be built given the state of contemporary technology.

1.3 Water Wheels

In all likelihood, the earliest tools employed by humankind for crushing or grinding seeds, nuts, and other food-stuffs consisted of little more than a flat rock, upon which the material was crushed by pounding with a stone or tree branch. The archaeological records show that as early as 30,000 years ago, Cro-Magnon artists employed the mortar and pestle to grind and mix the pigments they used to create their magnificent "cave-art".

Far more efficient than the flat rock or even the mortar and pestle was the handmill, which appears to have long pre-dated the agricultural revolution. The handmill consists of a flat rock, often hollowed or concave, on which the grain, seeds, or other materials is placed, and a grinding stone, which is rolled across the grain, thus reducing the grain to flour. Although the handmill is still, today, in use in many parts of the world, approximately 2,000 years ago humankind began to harness waterpower to turn the stones that ground its grain. They were probably the first tools for creating mechanical energy that replaced humans and animals.

The first description of a water wheel is from Vitruvius, a Roman engineer (31 BC–14 AD), who composed a 10 volume treatise on all aspects of Roman engineering. From classical times, there have existed three general varieties of water wheels: the horizontal wheel and two variations of the vertical wheel.

Waterpower was an important source of energy in ancient Chinese civilization. One of the most intriguing applications was for iron casting. According to an ancient text, in 31 AD the engineer Tu Shih invented a water-powered reciprocator for the casting of (iron) agricultural implements. Waterpower was also applied at an early date to grinding grain.

Renaissance engineers studied the waterwheel and realized that the action of water on a wheel with blades would be much more effective if the entire wheel were somehow enclosed in a kind of chamber. They knew very well that only a small amount of the water pushing or falling on a wheel blade or paddle actually strikes it, and that much of the energy contained in the onrushing water is lost or never actually captured.

1.4 Wind Mills

Over 5,000 years ago, the ancient Egyptians used wind to sail ships on the Nile River. While the proliferation of the water mill was in full swing, wind mills appeared to harness more inanimate energy by employing wind sails. Prototypes of wind mills were probably known in Persia (present day Iran) as early as 7th century AD with the sails mounted on a vertical axis. Towards the end of the 12th century, wind mills with sails mounted on a horizontal axis appeared in Europe; the first of this kind probably appeared in Normandy, England. These are post mills, where the sails and machinery are mounted on a stout post and the entire apparatus has to be rotated to face the wind.

Two centuries later the tower mill was introduced, enclosing the machinery in a stationary tower so that only the cap carrying the sails needed to be turned to the wind.

In 1854 Daniel Halliday obtained the first American windmill patent. His windmill had four wooden blades that pivoted and would self adjust according to wind speed. It had a tail which caused it to turn into the wind.

1.5 Renaissance Engineers

The credit for making pressure exerted by the atmosphere entirely explicit belongs to Otto von Guericke, who in 1672 published the famous book in which he described his air pump and the experiments that he made with it from the mid 1650s onwards. Once it was understood that atmosphere exerts pressure, it was a matter of creating a vacuum and utilizing atmospheric pressure to move the piston in a cylinder.

Denis Papin (1647–1712) a French physicist, mathematician and inventor is best known for his pioneering invention of the steam digester, the forerunner of the steam engine. He visited London in 1675, and worked with Robert Boyle from 1676 to 1679, publishing an account of his work in *Continuation of New Experiments* (1680). During this period, Papin invented the *steam digester,* a type of pressure cooker. He first addressed the Royal Society in 1679 on the subject of his digester, and remained mostly in London until about 1687, when he left to take up an academic post in Germany. While in Leipzig in 1690, having observed the mechanical power of atmospheric pressure on his 'digester', he built a model of a piston steam engine, the first of its kind.

Thomas Savery (1650–1715) was an English military engineer and inventor who in 1698 patented the first crude steam engine, based on Denis Papin's Digester or pressure cooker of 1679. His machine consisted of a closed vessel filled with water into which steam under pressure was introduced. This forced the water upwards and out of the mine shaft. Then a cold water sprinkler was used to condense the steam. This created a vacuum which sucked more water out of the mine shaft through a bottom valve.

In 1705 Papin developed a second steam engine, with the help of Gottfried Leibniz, using steam pressure rather than atmospheric pressure. Papin's steam engine was a breakthrough since Hero's reaction turbine of the second century BC never functioned in reality.

The Newcomen steam engine was the first practical device to harness the power of steam to produce mechanical work. Newcomen's first working engine was installed at a coal mine at Dudley Castle in Staffordshire in 1712. They were used throughout England and Europe to pump water out of mines starting in the early 18th century and were the basis for James Watt's later improved versions. Although Watt is far more famous today (due largely to Matthew Boulton's tireless salesmanship), Newcomen rightly deserves the majority of the credit for widespread introduction of steam power.

1.6 Industrial Revolution

Between 1780 and 1850, in a space of just seven decades, the face of England was changed by a far-reaching revolution, without precedent in the history of mankind.

Glasgow University had one of the Newcomen engines for its natural philosophy class. In 1763, one hundred years after the birth of Newcomen, this apparatus went out of order and Professor John Anderson gave the opportunity to James Watt (1736–1819) to repair it. After the repair and while experimenting with it, he was struck by the enormous consumption of steam; at every stroke, the cylinder and piston had to be heated to the temperature of boiling water and cooled again. This prevented the apparatus from making, with the available boiler capacity, more than a few strokes every minute. He quickly realized that the wastage of steam is inherent in the design of the engine and became obsessed with the idea of finding some remedy. From the discovery of Dr. Joseph Black (1728–1799), he deduced that the loss of latent heat was the most serious defect in the Newcomen engine. The work of James Watt is thus the application of science to engineering that led to the birth of industrial revolution.

In 1765 he conceived the idea of a separate condensing chamber for the steam engine to separate the condensation system from the cylinder, injecting the cooling water spray in a second cylinder, connected to the main one. When the piston had reached the top of the cylinder, the inlet valve was closed and the valve controlling the passage to the condenser was opened. External atmospheric pressure would then push the piston towards the condenser. Thus the condenser could be kept cold and under less than atmospheric pressure, while the cylinder remained hot. Important as the separate condenser idea was, in the fully developed version of 1775 that went into production, changes had to be more far-reaching. There was no spray, the condenser being immersed in a water tank and at each stroke the warm condensate was drawn off and sent up to a hot well by a vacuum pump which also helped to evacuate the steam from under the power cylinder. The still-warm condensate was recycled as feed water for the boiler.

Reciprocating machinery has inherent disadvantages at high speeds; they have practically disappeared in the modern day world. There are still steam locomotives operating in a few places, e.g., Fairy Queen, the oldest running vintage steam locomotive in the world built in the year 1855 by the British firm Kinston, Thompson & Hewitson for the British firm East India Railways and occasional reciprocating engines for producing small amounts of power in sugar mills, but otherwise they are gone. Internal combustion engines still thrive for transportation, power generation, and so on.

1.7 The Nature of This Book

The subject Theory of Machines is about 200 years old and has undergone tremendous changes during these two centuries. It began with the need to develop understanding of various links of disparate mechanisms, followed by Kinematics that explains displacements, velocities and accelerations inherent in these mechanisms. The reciprocating steam engines were bulky and rigid, their speeds were very low and rarely was a dynamic analysis needed. Their loads were calculated from dead weights and statics and applied to the pursuit of better design. By the time the basic concepts of Dynamics were perceived, the reciprocating steam engine was already on its way out, with about a century left to go, and Reciprocating Internal Combustion engines gained importance. Simultaneously, rotating steam turbines were favored for high capacities and high speeds. Jet engines and Gas turbines came into vogue nearly six decades ago. These new devices significantly enriched the subject Theory of Machines. Dynamics assumed an increasingly central role in design.

While reciprocating machinery formed the central theme of Kinematics and Dynamics studies, there were several other elements that became important in the study of the Theory of Machines, e.g., Cams in reciprocating engines, Gears in transmission units, Governors and Controls, etc. The studies of Reciprocating steam engine soon disappeared from the curriculum.

Initially Kinematics and Kinetics of Machinery was conducted by using graphical methods and where possible analytical methods until the advent of computer era in 1960s. With further advances in hardware and work centers the analysis and design was made simpler through simulation and visualization. Initially the designs were all through expensive and time consuming tests, they got gradually transformed to current day practice of simulation and optimization to arrive at the final prototype in the fastest time thus reducing the design cycle time and bringing new products to the market in the least possible time.

It is common practice nowadays for designers to use commercially available simulation tools or codes to achieve their finished designs. Most engineering instruction, however, continues to follow a conventional curriculum of classical theory, followed by computational tools, ending with amalgamation of this knowledge in order to meet industry standards. In this book, we attempt to make the time of instruction

more compact and to bring engineering students into the design industry in a faster and more efficient manner.

For an engineer to be most effective for current day applications, it is necessary to be well versed in the subject and have the ability to apply the basics to achieve advanced designs using tools that are fast acting and efficient. Therefore the Theory of Machines, taught usually in two semesters, is proposed to be given through simulation tools to make a young engineer most efficient in a shorter period of time. The two semester pattern can continue with additional tasks of practicing applications of industrial nature. To assist in this model of instruction and learning, the subject matter is developed here through Altair MotionSolve and MotionView. The teacher can instruct students in the basics of these tools to allow the students have imagination and develop industrial practice skills while learning the basics of the subject.

Our approach to such instruction is to teach the visualization of moving members of a machine, and correlation of these motions, to determine the most important kinematic parameters in their design. We see it as a more effective path than imagining a motion period through several 2D figures of the machine. We believe that it will more effectively help the beginning engineer understand the function and analysis of a reciprocating engine, cams that open and close valves, gears that produce uniform angular velocities between two shafts in a transmission unit, governors, links that provide reclining and movement of seats, earth moving elements handling large quantities of earth material, special purpose machine tools as in bottling systems, robots, etc., all machinery members and functions that one can imagine would have applications of Theory of Machines.

We will first look at kinematics and later extend our discussion to kinetics. The subject of kinetics will focus on important aspects of forces acting on machine members that will subsequently need to be recognized in design.

Note that this is not an instruction manual for any commercial tool. An appropriate manual can be given out separately and the teacher can, if it seems desirable, simultaneously teach the steps that will enable students to most effectively follow the subject matter through visualization. While the time-honored and conventional practice of drawing outlines and specifications on drafting tables will undoubtedly be quickly discouraged, students should be encouraged to do free hand sketching to express their ideas, particularly at the concept stage.